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A NASA  
High-Power  
Space-Based  
Laser  
Research  
and  
Applications  
Program

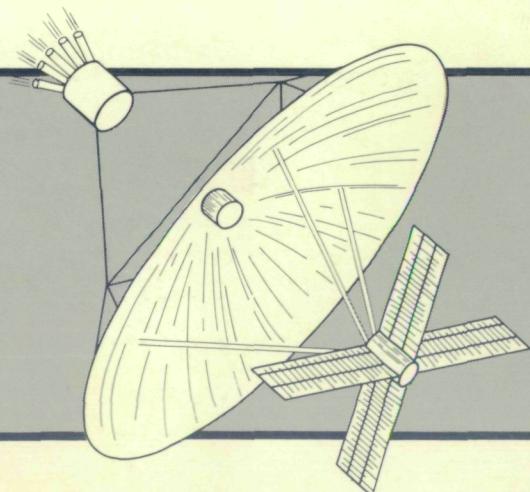
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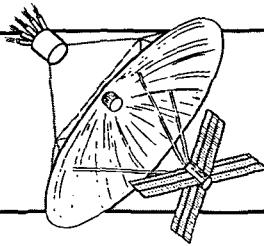
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NASA SP-464

# A NASA High-Power Space-Based Laser Research and Applications Program

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## **Preface**

Over the past 5 years, both Congress and the NASA Advisory Committees have shown a significantly heightened interest in the area of high-power lasers. In January 1980, testimony on NASA laser programs was presented before the Senate Subcommittee on Science, Technology, and Space. In May 1980, the Chairman of the House Committee on Science and Technology inquired about the NASA laser program with respect to planning and focus for civilian space use. The Chairman requested a study to unify laser development in the areas of space, energy, and defense.

In March 1979, the NASA Office of Aeronautics and Space Technology sponsored a High-Energy Laser Workshop to review the state of the art and identify the most promising applications for high-power lasers. In July 1980, a review of the NASA laser research program was presented to the High-Energy Laser Review Group (HELRG) of the Defense Advanced Research Projects Agency (DARPA). In September 1980, as a result of continued strong congressional interest, the NASA Administrator requested a review and reformulation of the NASA program on high-power lasers. This led to the formation, in October 1980, of the NASA High-Power Laser Working Group, with the following membership:

Frank Hohl,\* Chairman (LaRC)  
Lynwood Randolph, Acting Chairman (NASA HQ)  
Gerald Walberg (LaRC)  
Russell De Young (LaRC)  
Edmund Conway (LaRC)  
James Morris (LeRC)  
Robert English (LeRC)  
Joseph Randall (MSFC)  
Lee Jones (MSFC)  
Joseph Mangano (DARPA)

The group's purpose was to assess the current NASA program in the context of potential civilian and military applications and recommend a balanced program (complementing the DOD and DOE efforts) to provide a strong technological base for future civilian space applications.

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\*Dr. Hohl was taken ill during the course of the study, and his work was completed by Dr. Randolph.

In February 1981, this working group presented a status report to the Space Power and Electric Propulsion Subcommittee of the NASA Space Systems and Technology Advisory committee (SSTAC). The Subcommittee endorsed, in principle, an augmented program in high-power lasers. The present report summarizes the final recommendations and supporting rationale of the NASA High-Power Laser Working Group.

The authors wish to acknowledge the help of the NASA High-Power Laser Working Group, especially the contributions of Lynwood Randolph and Robert English, and the continued encouragement of Jerome Mullin. This report is adapted from the formal report of this working group.

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## ***Executive Summary***

The NASA High-Power Laser Working Group was formed in 1980 in response to the heightened interest in high-power lasers expressed by members of both the U.S. Congress and the NASA Advisory Committees. The group's task was to assess the current NASA laser research program in the context of potential civilian and military applications and to recommend a balanced program that would complement the research efforts of the Department of Defense (DOD) and the Department of Energy (DOE) and provide a strong technological base for future civilian space applications. This report presents the final recommendations and supporting rationale developed by this working group.

A review of potential NASA applications for high-power lasers is presented. Studies carried out since 1976 are shown to contain consistent, recurring themes involving potential high-payoff applications of high-power lasers for power beaming in space, spacecraft propulsion, and deep-space communications. Because of their small beam divergence and relatively short wavelengths, lasers have an unparalleled capability for transmitting energy in space. With diffraction-limited optics and a given transmitter size, a laser receiver is approximately 4 orders of magnitude smaller than a microwave system receiver. Studies of large orbital power stations that would beam power to distant satellites and orbital-transfer vehicles (OTV's) illustrate the great potential of solar-pumped lasers and show large transportation cost savings for orbital transfer if present optimistic estimates of laser and OTV thruster performance are realized (ref. 1). Beaming power from a central power station allows dramatic changes in the design of the receiving spacecraft. For instance, large arrays of solar cells can be replaced with relatively small laser beam collectors, which will dramatically reduce the overall size, mass, and control system requirements of the spacecraft. Not all applications require extremely high power levels. For instance, both power beaming from an orbiting space station to a nearby free-flying platform and communications over long distances within our solar system could be carried out effectively at power levels in the range of tens to hundreds of kilowatts. The payoff from the realization of any one of these potential applications would be extraordinary.

Comparison of technology characteristics of the NASA, DOD, and DOE laser programs shows little overlap because each has basically different mission requirements. For power beaming applications, NASA

must develop efficient, continuous-running, lightweight lasers. However, lasers developed by DOD and DOE tend to be pulsed or to have very short run times. DOD and DOE emphasis is on open-cycle systems and chemically or electrically pumped lasers. NASA missions require closed-cycle systems, which are well suited to solar-pumped lasers. There is, however, an area of strong common interest in pointing, tracking, and adaptive high-power optics. In this area, an efficient exchange of technology is being maintained. Overall, DOD and DOE funding levels are much higher than that of the NASA program, but the NASA program significantly complements the DOD-DOE effort by providing a strong technology base for continuous, high-power, closed-cycle systems and advanced concepts such as solar-pumped lasers, which are not being addressed by either DOD or DOE.

At present, electrically and chemically pumped lasers are well understood, but with the exception of new concepts such as the free-electron laser (FEL), they have a low probability of performance breakthroughs or large increases in efficiency. Nuclear-pumped lasers have shown great promise in recent years, but effective high-power space application requires integration of the laser into a gas core reactor. This technological

## **Technology Barriers**

### **Direct solar-pumped lasers**

Possible negative effects of elevated temperatures on quenching and recombination rates for iodide lasers

Degradation of total system efficiency due to lasant reprocessing requirements for closed-cycle operation

High threshold for continuous lasing of IBR

Depopulation of absorbing molecular level due to increase in triplet-state density in dye lasers

Potential limitation of continuous lasing due to collisional quenching and thermal broadening of upper states in liquid-Nd laser

### **Indirect (blackbody) solar-pumped lasers**

Filling of lower laser level due to heating of lasant in blackbody cavity

Potential reduction of laser output in CO/CO<sub>2</sub> transfer laser due to large radiative and collisional energy losses during transfer process

### **Transmission**

Lack of high-power high-temperature optics for long-term operation

### **Laser propulsion**

Need for experimental validation of thruster analyses

Uncertainty regarding basic absorption mechanisms

Potential thruster design problems due to high plasma temperatures

### **Laser-to-electric conversion**

Low efficiency and/or high mass of demonstrated concepts

High-conductivity low-temperature plasma (about 16 000 K) for laser magnetohydrodynamic conversion not yet demonstrated

Need to lower average electron energy range for reverse free-electron laser (RFEL)

Potential excessive mass of RFEL

Need to demonstrate high internal efficiencies for optical diode

step would require large resource outlays and should not be carried out until the competing solar-energized laser option has been researched in sufficient depth to assess its future potential. Accordingly, the current NASA program emphasizes direct solar-pumped lasers, with modest efforts in blackbody solar lasers, high-efficiency converters, and laser propulsion.

The principal technology barriers in the current NASA laser research program are summarized in the table on the facing page. They involve (1) the achievement of higher efficiencies and closed-cycle operation for direct solar-pumped lasers, (2) the maintenance of population inversions and the achievement of an efficient optical-vibrational excitation transfer for indirect solar-pumped lasers, (3) the achievement of long-term, high-power operation of transmission optics, (4) a basic understanding of laser thruster phenomena for laser propulsion, and (5) the development of higher efficiency laser-to-electric converters.

### Program Element Milestones

Program elements	Year									
	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
<b>Solar-pumped lasers</b>										
Demonstration of blackbody laser .....					▲					
Demonstration of continuous-wave solar laser .....						▲				
Demonstration of 1-kW solar laser .....							▲			
Demonstration of 5% efficient solar-energized laser .....								▲		
<b>Laser energy conversion</b>										
Selection of primary-candidate laser-to-electric converters .....				▲						
Demonstration of 50% laser-to-electric converter .....							▲			
Characterization of H <sub>2</sub> plasma .....					▲					
Thruster cooling experiment .....						▲				
100-kW laser thruster experiment .....								▲		
<b>Laser power transmission optics</b>										
Identification of critical-technology elements .....					▲					
Complete development of critical optical components .....								▲		
<b>Space-based laser systems studies</b>										
Multiple applications for space-based lasers .....					▲					
Benchmark high-power laser system .....						▲				
100-MW space-based system design .....								▲		

To address these technology barriers and to provide for balanced technology development in all areas of first-order importance, the program shown in the table on the preceding page is proposed by the working group. This program provides increased emphasis on blackbody solar-pumped lasers, laser propulsion, and laser-to-electric energy conversion while maintaining the direct solar-pumped laser effort at a level consistent with significant progress. A small program in electrically pumped lasers is maintained to address advanced concepts such as the free-electron laser. The transmission element of the program consists of small-scale systems studies and DOD-NASA coordination in the early years, with increased emphasis after 1985 on developing transmission technology unique to NASA's needs. A systems study element is included to provide program focus.

This program emphasizes research on basic technological issues and is not hardware-oriented. It is unique to NASA in that the program elements are not presently being studied by DOD or DOE. Each program milestone identifies a programmatic objective in its technology area. Taken together, these milestones point to a well-developed research and technology base for the implementation of NASA missions in the 1990's and beyond.

## ***Introduction***

This report summarizes the recommendations of the NASA High-Power Laser Working Group which met in 1980. Potential applications of high-power lasers are discussed which might fulfill the needs of future NASA missions, and the technology characteristics of the NASA, Department of Defense (DOD), and Department of Energy (DOE) laser research programs are outlined. Since the funding level of the NASA laser research program is low compared to those of DOD and DOE, the latter programs must be followed carefully and the available technology used in support of NASA program goals. The current status of the NASA programs on lasers, laser receivers, and laser propulsion is discussed, and recommendations are presented for a proposed expanded NASA program in these areas. Program elements that are critical are discussed in detail. This proposed expanded research program should lead to the future achievement of a level of space-based power generation and distribution which will be adequate for NASA mission requirements into the next century.

## **Potential Applications for High-Power Lasers**

Over the past several years, a number of studies have identified promising applications for high-power lasers. References 1 through 15 constitute a representative sampling of studies published since 1976 and are indicative of the high level of interest and the types of applications most often discussed in relation to the NASA program. Although these studies differ significantly with regard to technical depth and sometimes arrive at conflicting conclusions, there are several consistent, recurring themes.

For instance, applications involving power beaming in space, laser propulsion for spacecraft, and deep-space communications are identified repeatedly. These applications are often cited as ways of reducing the cost of space power and propulsion, which is a necessary prerequisite to the aggressive development of near-Earth space. The application that most consistently shows a high potential payoff is laser propulsion for orbital-transfer vehicles. The beaming of power from a large central space power station to a number of spacecraft seldom shows a large cost saving, but it does allow dramatic changes in the design of the receiving spacecraft. For instance, large arrays of solar cells can be replaced with a relatively small laser beam collector, which will dramatically reduce the overall size, mass, and control system requirements of the spacecraft.

Because of their small beam divergence and relatively short wavelengths, lasers have an unparalleled capability for transmitting energy in space. This is illustrated in figure 1, which shows the product of transmitter and receiver diameters ( $D_t D_r$ ) as a function of transmission range for various wavelengths, under the assumption of diffraction-limited optics (ref. 1). Note that for a given transmission range, the laser receiver-transmitter diameter ( $D_t D_r$ ) is approximately 4 orders of magnitude smaller than that for a microwave system. This advantage of laser energy transmission has motivated studies of solar-power satellite (SPS) systems, in which the power is beamed to Earth using lasers rather than microwaves. In one such study of a 10-GW system (ref. 14), the total program costs for laser and microwave transmission were comparable, but the area required for the receiver on Earth was 200 acres for the laser system compared with 80 000 acres for the microwave system.

Figures 2 through 4 (ref. 1) illustrate one of the most thoroughly studied applications of high-power lasers in space, a large central power station in geosynchronous orbit which beams power to remote users. The figures are

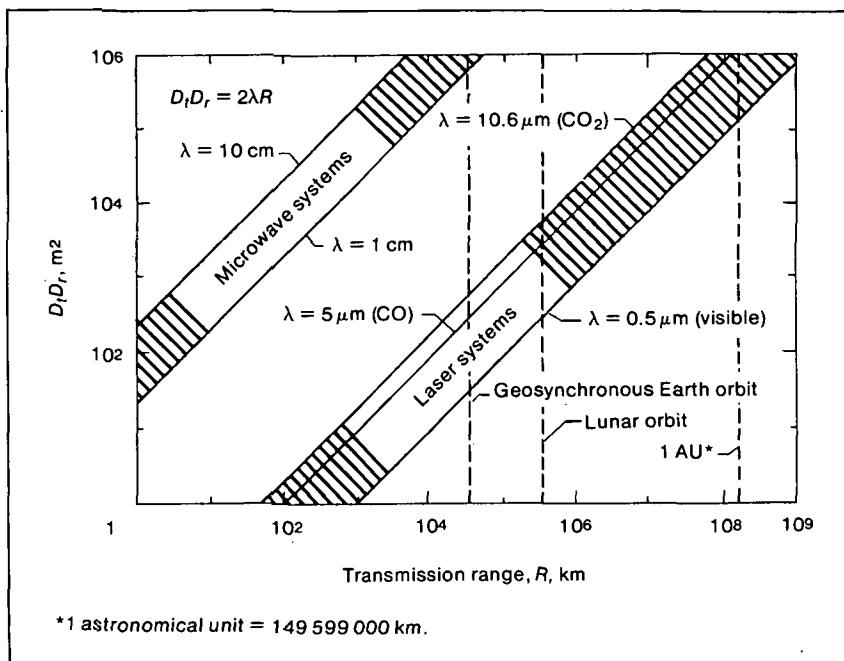


Figure 1.—Transmitter/receiver diameter product as a function of transmission range.  $\lambda$  = wavelength. (From ref. 1.)

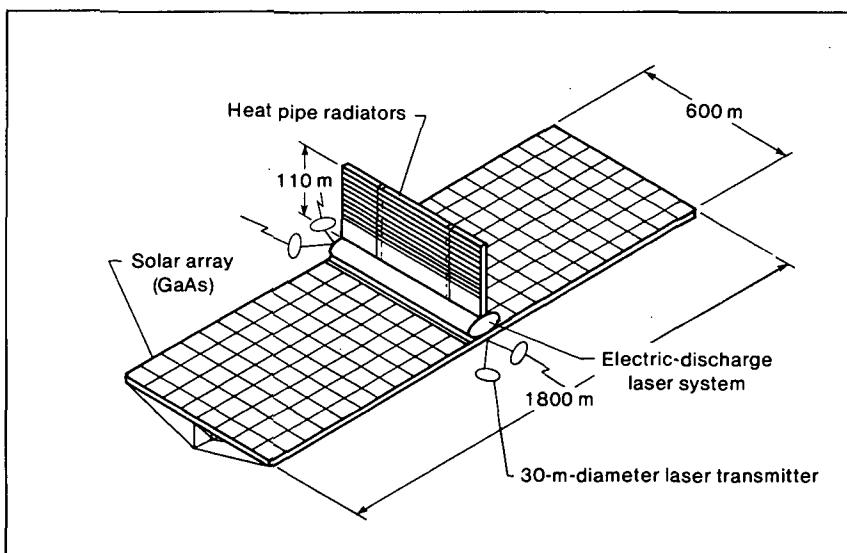
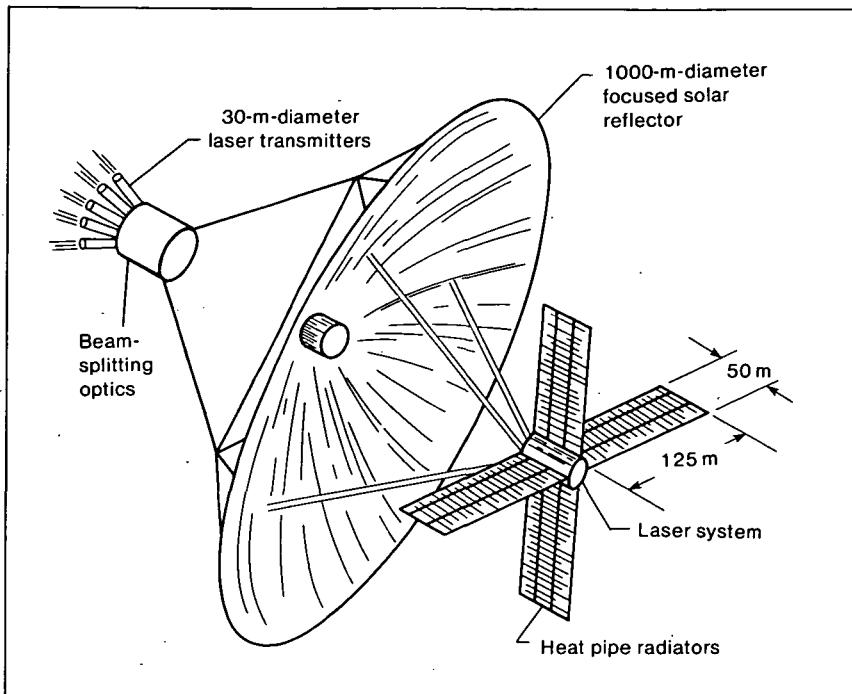


Figure 2.—Photovoltaic EDL central power station concept. 100-MW laser. (From ref. 1.)



*Figure 3.—Direct solar-pumped laser power station concept. 100-MW laser. (From ref. 1.)*

schematic representations of three power station concepts, an electric discharge laser powered by a photovoltaic array (fig. 2), a solar-pumped laser (fig. 3), and a nuclear-pumped laser that is an integral part of a gas core nuclear reactor (fig. 4). Each power station concept was designed to produce a laser beam power of 100 MW. All three power station concepts are very large structures and probably involve comparable levels of difficulty with regard to deployment or erection in space. Although all three concepts are large, they are large for different reasons. The photovoltaic electric-discharge laser (EDL) system is dominated by the solar-cell array, the solar-pumped laser system is dominated by the solar reflector, and the nuclear-pumped laser system is dominated by the radiator array required to dissipate the excess heat produced by the reactor. Of the three concepts, the technology for the photovoltaic EDL system is by far the most advanced. Such a system could probably be built, but, it would be relatively expensive. Hence, the photovoltaic EDL system is the most "real" of the three. The nuclear-pumped laser has received considerable study, and a fairly strong technology base exists for both the laser and the gas core reactor as individual concepts. What has not been demonstrated is the integration of the reactor and laser into a single unit, as shown in

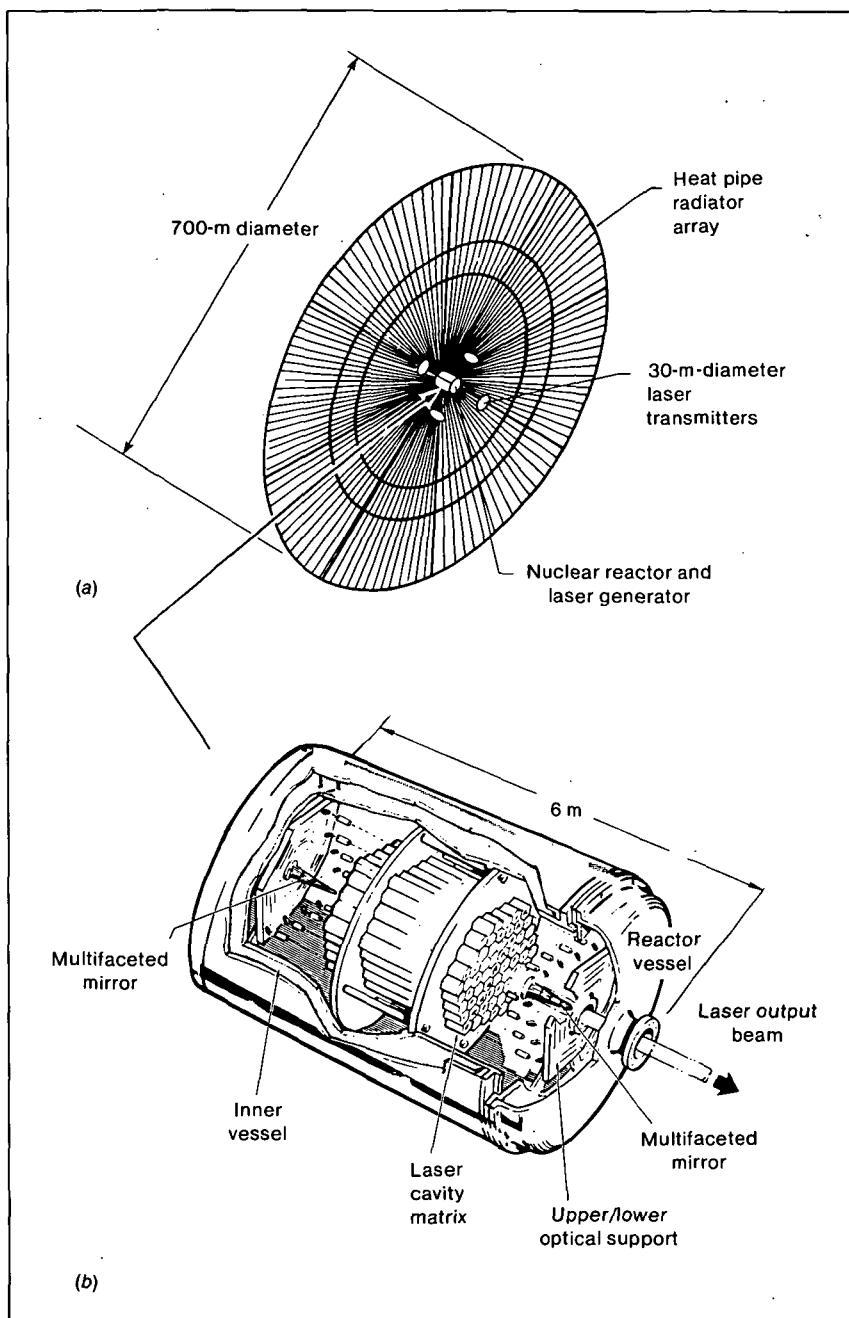
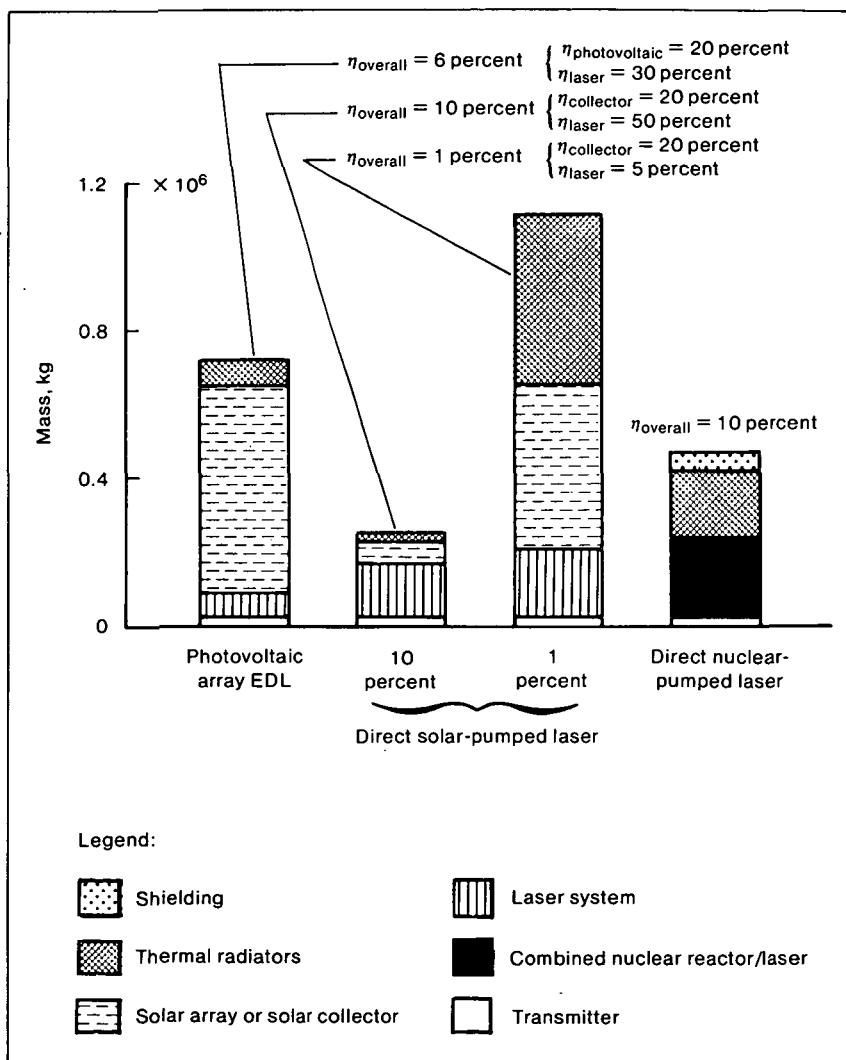


Figure 4.—Direct nuclear-pumped laser power station concept. 100-MW laser. (From ref. 1.) (a) Complete system. (b) Conceptual  $\text{UF}_6$  gaseous nuclear-pumped laser reactor.

figure 4. This is a crucial technological step for the space-based nuclear-laser power station, and would require a level of funding well beyond the scope of any foreseen NASA program in high-power lasers. The solar-pumped laser is the newest of the three concepts. As will be discussed subsequently, both a direct solar-pumped gas laser and a blackbody-pumped gas laser have been demonstrated in the laboratory, but the technology for these concepts is in a very early stage of development.



*Figure 5.—Comparison of advanced power station system masses. 100-MW laser. (From ref. 1.)*

Figures 5 and 6 present comparisons of the three concepts (photovoltaic solar, direct solar, and direct nuclear) in terms of mass and cost (ref. 1). These comparisons show the nuclear- and solar-pumped systems to be potentially very attractive if their respective technology barriers can be overcome. The efficiencies ( $\eta_{\text{overall}}$ ) referred to in figures 5 and 6 are the

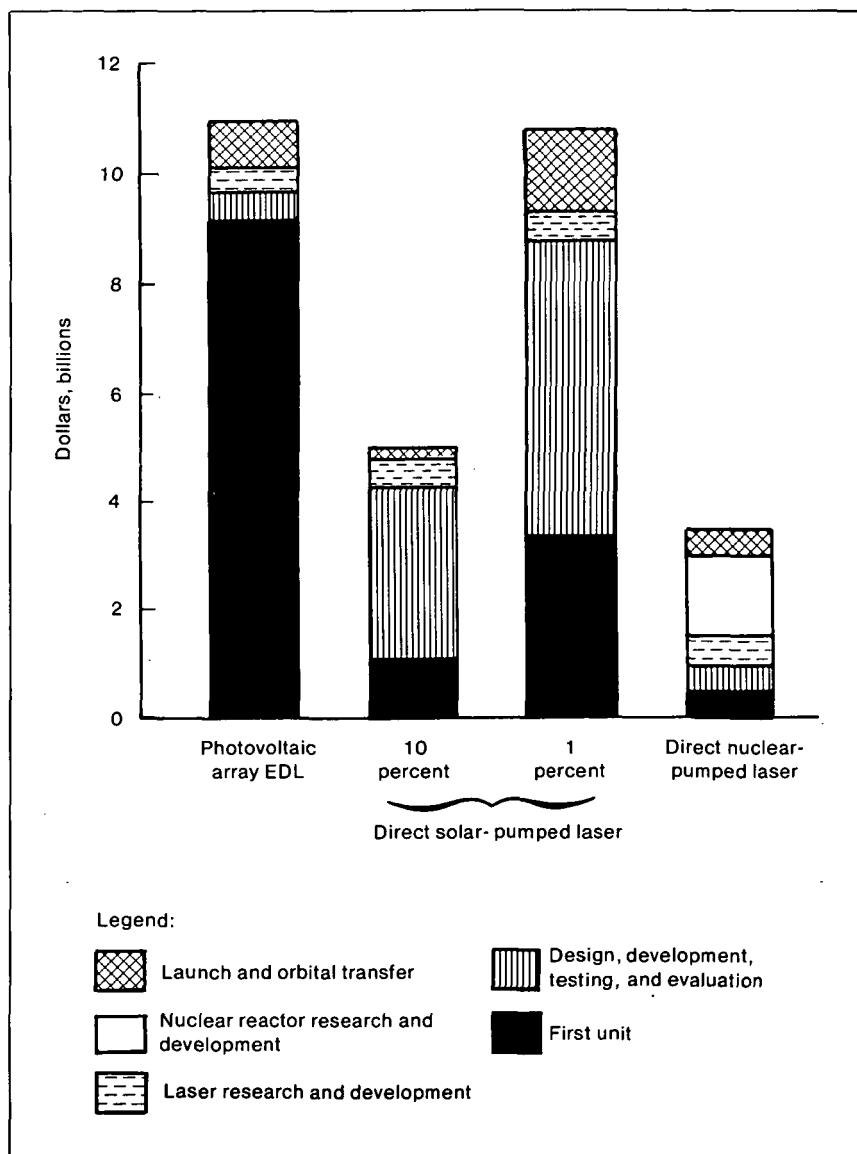


Figure 6.—Comparison of advanced power station system costs. 100-MW laser. (From ref. 1.)

"front end" efficiencies of each system; that is, the percentage of the incident solar or nuclear energy which is converted into laser light. The 6-percent value for the photovoltaic EDL system is slightly optimistic, but is probably representative of what could be achieved by an aggressive development program. The 10-percent value shown for the nuclear laser is optimistic, but such values have been projected by competent investigators. The 20-percent value of  $\eta_{\text{collector}}$  for the solar-pumped system reflects present estimates that no more than approximately 20 percent of the solar spectrum will be absorbed by the lasant. The two values of 10 percent and 1 percent shown for  $\eta_{\text{overall}}$  for the solar laser represent optimistic and pessimistic present predictions. The 1-percent value can almost certainly be achieved. The 10-percent value represents a difficult (but not patently impossible) technical challenge. As can be seen from these two figures, a 10-percent-efficient solar laser is a very attractive system. In a subsequent section of this paper, it will be shown that several candidate lasants currently under study have potential front-end efficiencies approaching 10 percent.

As mentioned earlier, laser propulsion for orbital-transfer vehicles (OTV's) is consistently identified as a high-payoff application. Figure 7 (ref. 1) presents a schematic representation of a typical laser-propelled OTV. In this concept, the laser light is focused and directed into the thrust chamber of the rocket, where it is absorbed and increases the internal

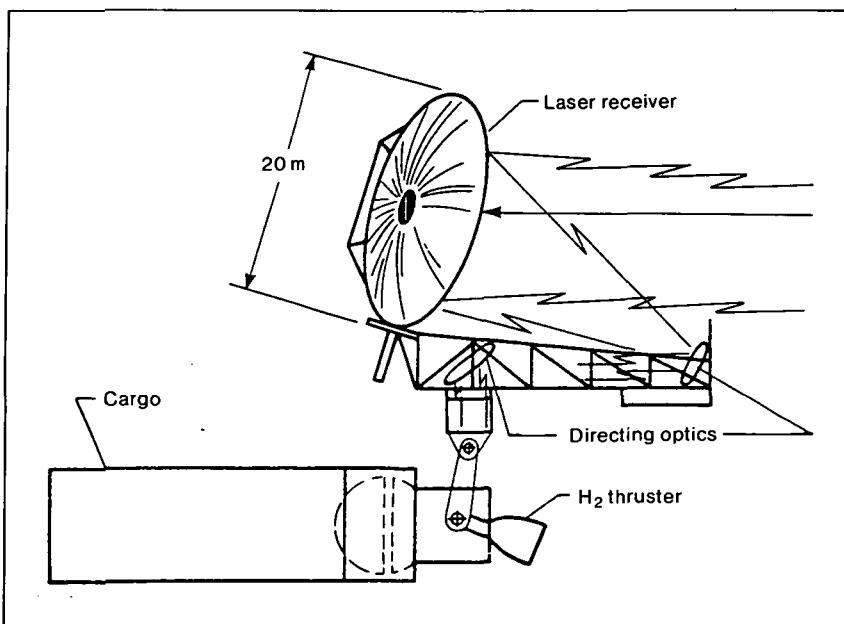


Figure 7.—Laser thermal propulsion system. (From ref. 1.)

energy of the working gas, which is H<sub>2</sub> in this application. The heated H<sub>2</sub> is then expanded through a conventional rocket nozzle to produce thrust. Theoretical studies predict a specific impulse between 1000 and 2000 sec for such a laser thermal-propulsion system. This is a highly desirable specific-impulse range for OTV applications, which cannot be achieved by either chemical systems (which have a maximum specific impulse of about 500 sec) or electric-ion-bombardment thrusters (which have a minimum specific impulse of about 2000 sec). In reference 1, the costs of supporting an early space industrialization scenario featuring a heavy leo-to-geo (low Earth orbit to geosynchronous Earth orbit) traffic model were compared for the system shown in figure 7 and for an advanced chemical OTV. The transportation cost for the laser thermal OTV (including the cost of the central laser power station) was one-half that calculated for the chemical OTV system. Cost savings of this magnitude and greater are often predicted. One of the most quoted studies (ref. 13) showed chemical-to-laser OTV transportation cost ratios ranging from 2.4 to 6.9, with laser systems producing greater cost savings as OTV traffic increased.

Although most studies of laser power beaming have considered very high power systems, there are interesting applications at modest power levels. For instance, conceptual studies have shown that a solar-pumped laser producing a beam power of 100 kW would require a collector diameter of only approximately 42 m and could weigh as little as 10 000 kg. Such a system might be constructed on a manned space station and could be used to beam power to a nearby free-flying spacecraft. The free-flying spacecraft might be a platform for science or materials-processing experiments that could not tolerate the vibration and contamination environment of the large space station. A laser-receiving mirror with a diameter of only 8 m would be required on the free flyer, and this combined with a 50-percent-efficient solar-to-electric conversion system would provide 50 kW of electrical power. By contrast, an 8- by 80-m photovoltaic array attached to the free flyer would be required to provide the same power. Hence, laser power beaming could completely change the character of the free-flying platform from a large, flimsy structure having low natural frequencies and difficult control problems (for the photovoltaic system) to a relatively small, compact, easily controlled platform. The same 100-kW laser system, when combined with laser thermal propulsion, would provide the free flyer with thrust levels of approximately 5 N, which could be used for attitude control, maneuvering to and from the space station, and modest orbital transfer.

Another potential application for modest-power lasers is long-distance space communication. Because of its small beam divergence, the laser can pinpoint regions of deep space that are small compared to those that can be investigated by microwave. Since laser radiation is coherent, it is more easily detectable than spontaneous light. Vehicle communications over long distances within our solar system could be more cost-effective with

lasers than with microwave systems. For instance, high-data-rate communications of  $5 \times 10^6$  bits/sec (typical of continuous television) over 40 AU (the distance to Pluto) with a 1-m-diameter transmitter and a 10-m-diameter receiver would require the following beam power levels:

Microwave .....	$2 \times 10^6$ W
CO <sub>2</sub> laser (10.6 $\mu$ m) .....	$2 \times 10^3$ W
Visible laser .....	$10^2$ W

It can be seen that a large number of potential space applications exist for high-power lasers. Although no single application can be identified which requires the immediate development of these devices, many of these applications could revolutionize man's ability to explore and exploit space. Some of these applications are bold enough to invite a degree of skepticism; however, if one of these or a similar application (not yet conceived) should be realized, the payoff would be extraordinary.

## ***Technology Characteristics of NASA, DOD, and DOE Laser Programs***

The technology characteristics of the NASA and DOD-DOE laser programs are contrasted in table I. The DOD level of effort in high-power lasers was 2 orders of magnitude greater than that of the NASA program and the DOE effort was 1 order of magnitude greater. Since these programs are substantially larger than NASA's, the NASA program must draw from those of DOD and DOE wherever possible. Only those program elements unique to NASA missions must be researched, and the flow of technology from DOD and DOE should be relied on to support common areas of interest.

It is important to consider the general characteristics of the NASA and DOD-DOE laser effort. For power-beaming applications, NASA must develop efficient, continuous, lightweight, low-cost lasers. However, DOD-DOE lasers tend to be pulsed or to have very short run times. DOD and DOE are designing open-cycle systems, especially for chemical lasers, whereas NASA must use a closed-cycle laser to achieve a long run time. The excitation sources for DOD-DOE lasers are basically either chemical or electrical. For NASA needs, present indications are that solar or nuclear excitation may have the highest payoff. Both NASA and DOD-DOE are interested in all laser wavelengths, but wavelengths in the visible are most desirable; the major requirement is high power at any wavelength. DOD-DOE lasers tend to produce short, concentrated bursts of radiation for target location or destruction; thus receiver technology is

**Table I.—Characteristics of NASA and DOD-DOE Laser Programs**

DOD-DOE	NASA
Short run time (seconds)	Long run time (years)
Open cycle	Closed cycle
Chemical or electrical excitation	Solar or nuclear excitation
All wavelengths (visible to near-IR)	All wavelengths
Receiver: target for location and/or destruction	Receiver: efficient converter
Accurate pointing (adaptive optics)	Accurate pointing (adaptive optics)
Budget:	
DOD (FY 1980) .....	\$211 million
DOE (FY 1981). ....	\$24 million
	\$1.6 million

not a major program element. Conversely, NASA's interest is in efficient conversion of laser radiation to thrust, electricity, or storable energy. Both NASA and DOD-DOE have a common interest in high-power optics, pointing/tracking, and adaptive optics. In this area, there is a strong overlap of interest, which points to a need for efficient exchange of technology to eliminate any duplication of effort.

Specific DOD laser weapons programs that include some of the previously discussed NASA-DOD technology commonality are outlined below.

1. Talon Gold is a program to develop and test firing control and precision beam direction for space-based laser systems.
2. Project Alpha will develop a large, ground-based chemical laser with high enough power for space applications.
3. The Large Optics Demonstration Experiment will integrate advances in large mirrors, high-bandwidth fine tracking, beam stabilization, and advanced structures into an ultra-high-performance electro-optical system.

The direct impact of DOE high-power laser programs on NASA mission requirements is very small because DOE applications of fusion and isotope separation require laser systems that would serve no apparent use in typical NASA systems. That is, DOE needs high peak power in very short pulses for fusion, whereas NASA requires continuous high power. However, NASA has some interest in DOE-supported basic research on new laser mechanisms and on the interaction of intense coherent radiation with solids and gases.

At the present time, DOD-DOE high-power laser programs are very active in developing a reservoir of concepts, supporting technology, and trained scientists. It is to NASA's advantage to develop its own high-power laser program while making full use of research results generated by other agencies, and also to develop in parallel those elements such as converters and propulsion systems which are unique to NASA missions.

## **Technology Status for High-Power Laser Systems and Converters**

The present status of research on high-power lasers and laser energy converters is summarized in tables II and III. The order of presentation in table II is from the oldest and best-known concepts (electrically pumped lasers) to the newest and least well understood but potentially most advantageous systems for space applications (solar-pumped lasers).

Electrically pumped lasers are well understood, and large efforts by DOD and DOE are being carried out in this area. These lasers tend to have low system efficiency because there are several energy conversion

**Table II.—Status of Research on Potential Space-Based High-Power Laser Systems**

### **Electrically pumped lasers**

Solar cells available to provide electric energy for laser pumping

Each component of laser system reasonably well known

Although present overall efficiency is highest, potential for substantial gains in efficiency is lowest

Free-electron lasers show great promise

### **Chemical lasers**

Technology known and demonstrated for high pulse power

Represents least-risk, short-term approach

Overall efficiency low; technology relatively mature

Large quantities of reactant required

### **Nuclear-pumped lasers**

1-kW lasing achieved in  $^3\text{He}$ -Ar system at  $1.79 \mu\text{m}$

Scaling to higher power for  $^3\text{He}$  systems reasonably well known

Preliminary studies of  $^{235}\text{UF}_6$ -pumped lasers and  $^{235}\text{UF}_6$  gas core reactors started, but interface between laser and reactor still to be developed

### **Indirect solar-pumped lasers (blackbody-pumped)**

Blackbody-pumped  $\text{CO}_2$  or  $\text{N}_2$  with energy transferred to  $\text{CO}_2$  produced lasing at  $10.6 \mu\text{m}$

Potential highest efficiency system; high power yet to be demonstrated

Good potential for demonstration of high-power lasing

Lasing achieved in laboratory

### **Direct solar-pumped lasers**

First solar-pumped  $\text{C}_3\text{F}_7\text{I}$  gas laser achieved at  $1.3 \mu\text{m}$

Fundamental research under way to identify other gas and liquid solar-lasant candidates

Present efficiency is low; however, efficiency potential is high

**Table III.—Status of Research on Potential Laser Energy Converters**

Converter	Type	Wavelength, μm	Theoretical efficiency	Status	Limitations
<b>Laser to propulsion</b>					
H <sub>2</sub> plasma	Inverse Bremsstrahlung*	0.5–10	—	Research	Plasma dimension unknown
Ablation plasma	Inverse Bremsstrahlung*	0.1–10	—	Conceptual	Necessary laser intensity unknown
<b>Laser to electric power</b>					
Photovoltaic	GaAs	<0.9	0.45	Research	High cost; Power density unknown
Optical diode	Metal-oxide-metal	0.2–10	>0.50	Research	Characteristics unknown
Thermophotovoltaic	Blackbody cavity at 3000 K	All	0.50	Research	Size scaling unknown
Thermoelectric laser energy converter (TELEC)	Thermoelectric	All	0.42	Research	Scaling uncertain
Heat engines	Mechanical	All	0.65	Research	High-temperature materials necessary
Photochemical	Semiconductor	0.6	0.30	Research	Scaling, lifetime uncertain
Laser magneto- hydrodynamics (MHD)	Plasma	All	>0.50	Research	High-power operation unknown
Reverse free- electron laser (RFEL)	Electron beam	All	>0.50	Conceptual	Characteristics unknown

\*Laser absorption mechanism (plasma).

steps, and low power-to-weight ratios because this energy conversion equipment is heavy. Although electrically pumped laser system efficiencies are the highest presently available (about 6 percent front-end efficiency), the probability of substantial improvements in efficiency is the lowest compared to other potential laser systems. The free-electron laser is a new concept which could have a very high electrical-to-optical efficiency and great potential for continuous-wave (CW) high-power operation. An initial assessment has defined a space-based free-electron laser design and designated those areas needing further research.

Chemical laser technology is well known and proven, and is being heavily incorporated into DOD programs because it offers a low-risk, near-term approach to space-based high-power pulsed lasers. The overall cost appears to be high because chemical reactants must be replaced

often. There is no active NASA research in this area because chemical lasers appear to be unsuited for NASA needs.

Nuclear-pumped lasers have shown great promise in recent years based on the developments that led to 1-kW continuous-wave lasing of  $^3\text{He}-\text{Ar}$  at  $1.79\ \mu\text{m}$  (ref. 16). The scaling of  $^3\text{He}$  systems is reasonably well known. The greatest payoffs in nuclear pumping occur when the laser is an integral part of a gas core reactor. Preliminary studies with  $^{235}\text{UF}_6$ -pumped lasers and gas core reactors have been started, but the interface between laser and reactor has not yet been developed. This interface program has been terminated due to the large resource requirements (funds, manpower, and facilities) needed to research a gas core reactor and laser.

Indirect or blackbody solar-pumped lasers may offer the highest system efficiency of any potential space laser system. Work has begun to explore several blackbody laser concepts. Such systems have good potential for high-power lasing. Recently, blackbody radiation has been used to excite  $\text{CO}_2$  and produce lasing (ref. 17). Lasing has also been demonstrated using heated  $\text{N}_2$  to collisionally excite  $\text{CO}_2$ , which in turn lased at  $10.6\ \mu\text{m}$  (ref. 18). Much work needs to be done to extend this to higher powers.

Direct solar-pumped lasers using solar-simulator excitation of  $\text{C}_3\text{F}_7\text{I}$  have been demonstrated recently (ref. 19). Research on this and other more advanced gas and liquid lasers is under way. These lasers require the fewest conversion steps between sunlight and laser energy because they produce the laser inversion during the absorption of solar radiation. Although efficiency is currently low, potential system efficiencies could exceed that of electrically pumped lasers.

Research on techniques for converting and using laser power at a receiver currently is being pursued at a very low level. Table III outlines the current state of potential laser energy converters. Of the listed converters, only the boiler heat engine has reached the development state. This indicates the critical need for enhanced research in this area.

## **Evolution of the NASA Program**

In 1972, following the informal recommendation of a NASA Research and Technology Advisory Committee Working Group, the NASA Office of Aeronautics and Space Technology (OAST) established a High-Power Laser System Program to capitalize on the power and propulsion systems capabilities at Lewis Research Center, the laser physics and converter research at Ames Research Center, and the laser beam propagation and nuclear-pumped laser research at Langley Research Center. A bibliography included at the end of this report indicates the scope of the work performed under this program. The most prominent NASA application of lasers would be the generation of large amounts of power in space (or on Earth), the transmission of that energy over long distances (exploiting the

collimation, coherency, and monochromaticity of lasers), and the ultimate conversion of that energy for power and propulsion.

Between 1972 and 1979, the NASA program investigated the feasibility of space-based, multimegawatt, CW, closed-cycle laser systems through in-house and contracted efforts that were coordinated with DOD research efforts. Most of the effort was directed toward the electric-discharge CO<sub>2</sub> and nuclear-pumped laser technologies, since those were space-compatible technologies that met NASA mission requirements as identified by early systems studies. The research effort on nuclear-pumped lasers resulted in the development of a 1-kW <sup>3</sup>He-Ar nuclear-pumped laser. Also, a critical <sup>235</sup>UF<sub>6</sub> gas core reactor was demonstrated by the Los Alamos Scientific Laboratory under contract to NASA (ref. 20). The next technology barrier would be a costly step involving integration of a gas laser with a fissioning gas core reactor. This was judged to be premature, since the potentially simpler solar-energized laser option had not been researched sufficiently to assess its future potential. Large adaptive optical systems and phase locking were also investigated and were shown to be capable of transmitting and preserving the coherency of high-power laser beams. The DOD program has placed heavy emphasis on adaptive optics and phase locking and is aggressively developing these technology areas. Preliminary studies and experiments on laser propulsion and electrical conversion were also begun by NASA.

By 1979, as a result of a series of workshops and conferences, it was decided that the limited funds available for the NASA program could be utilized best by phasing out the work on conventional electrically pumped and nuclear-pumped lasers and emphasizing research on solar-pumped systems, which are simpler but could be as efficient as electrically pumped lasers. The rationale was that this would bring the technological base for solar-pumped lasers to a level of definition comparable with that for the electrically pumped and nuclear-pumped concepts, and this would allow a more realistic appraisal of the potential applicability of the various laser systems to future NASA missions. The recommended shifts in emphasis were accomplished, and accordingly the 1982 NASA laser program consisted primarily of research on solar-pumped lasers, with modest efforts on high-efficiency converters and laser propulsion and a small continuing effort on advanced electrically pumped laser concepts such as the free-electron laser.

## **Content and Technology Barriers in the Current NASA Program**

**Lasers.**—The first solar-pumped gas laser has been demonstrated using C<sub>3</sub>F<sub>7</sub>I (ref. 19). This system absorbs strongly from 250 to 290 nm, which amounts to approximately 1 percent of the total solar spectrum.

The branching ratio into the upper laser level is near unity, which produces lasing at  $1.315\text{ }\mu\text{m}$  in atomic iodine. In figure 8 a comparison is shown between the output of the xenon arc solar simulator (input to laser) and the output of the lasant at  $1.3\text{ }\mu\text{m}$ . Also shown is a computer simulation of predicted laser output from a kinetic code. The good agreement shown between the experimental results and the theoretical prediction indicates an accurate mathematical modeling of the principal physical phenomena. Hence, the present analytical techniques can be used to investigate generically similar lasants theoretically. Laser power output has been shown to peak at about 15 torr  $\text{C}_3\text{F}_7\text{I}$ . In addition to lasant pressure, other scaling parameters such as tube length, simulator intensity, and laser output mirror reflectivity are being investigated. This laser's solar-power efficiency is 0.1 percent with an initial peak output power of 4 W.

Presently,  $\text{C}_3\text{F}_7\text{I}$  is the primary lasant candidate under study. For medium-power operation in space,  $\text{C}_3\text{F}_7\text{I}$  could be useful; however, for the multimegawatt systems proposed in studies, collector size may make this lasant impractical. However,  $\text{C}_3\text{F}_7\text{I}$  is important because it is typical of the class of iodide lasants known as photodissociating RI molecules, where I represents iodine and R is any radical. One RI molecule currently being investigated is  $(\text{CF}_3)_2\text{AsI}$ . Further research is being performed with  $\text{C}_3\text{F}_7\text{I}$  because it is the only RI molecule currently lasing with solar

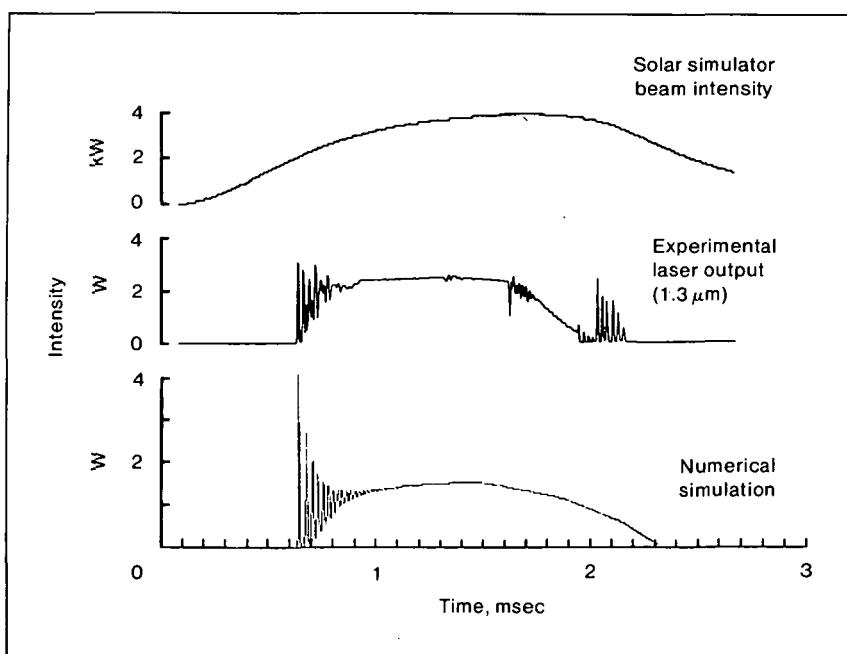


Figure 8.—Comparison of typical laser output and numerical simulation.

pumping and because research with the *RI* molecule could lead to the development of other potentially useful lasants.

There are two questions central to the utility of *RI* lasants.

1. How will elevated-temperature operation of the lasant affect critical rate coefficients such as quenching of iodine and recombination of *R* with iodine, and thus alter high-power efficiency and system parameters?
2. How will the total system efficiency be perturbed by reprocessing *R* and *I* into *RI* as required for closed-cycle operation?

Measurements of elevated-temperature rate constants will be made in the laser cavity to provide data for computational scaling of an *RI* laser to high power. In addition, a theoretical study of the rate of formation of *R*<sub>2</sub> in the laser and of the energy needed to reconstitute *RI* outside the cavity will be performed to complete the first molecular-level study of the efficiency and life of a closed-cycle direct solar-pumped laser.

To expand our knowledge of solar-lasant candidates, a computational effort has begun which will help find and evaluate new solar-pumped lasants. Initially, this program is focusing on *RI*-type lasants and is using semiempirical quantum-mechanical methods to evaluate absorption spectra, dissociation yields, and the excitation of products. The goal is to find *RI* molecules that absorb strongly in the visible or near-infrared, dissociate simply into *R* and *I*, and result in electronically excited iodine. This research effort is being carried out under a grant from NASA by the Institute for Molecular Quantum Mechanics at the University of Florida.

Other potential direct solar-pumped lasants being thoroughly researched are iodine bromide, dyes, and neodymium in a liquid solution. Iodine bromide (IBr) absorbs over a broad range of the visible solar spectrum. An estimate of the maximum solar efficiency (based on solar-absorption efficiency and the solar photon to laser photon energy ratio) is 2.7 percent. Thus, IBr may be much more efficient than C<sub>3</sub>F<sub>7</sub>I, and some research results support this assessment (ref. 21). However, IBr seems to be limited by a high threshold for continuous lasing due to quenching of excited bromide by I<sub>2</sub>, Br<sub>2</sub>, and IBr. Using the mature modeling techniques developed for the pulsed IBr laser, experiments and calculations will explore techniques for exceeding the threshold for continuous lasing.

Rhodamine 6G is a dye that absorbs over a broad range of the solar spectrum and has a maximum estimated solar efficiency of approximately 5.6 percent. Optically pumped liquid-dye lasers are normally pulsed because a large triplet density builds up and depopulates the absorbing molecular ground state. Continuous-wave dye lasers require high-speed lasant flow perpendicular to the cavity and high-intensity (generally laser) optical pumping. The key problem in achieving an efficient, continuous, solar-pumped dye laser is to reduce the triplet density and repopulate the

absorption ground state. Chemical additives that would reduce this triplet density are being investigated experimentally in order to lengthen the laser pulse and permit slowly flowing, continuous lasing.

The neodymium ion exhibits broad absorption in the visible spectrum and has an estimated maximum solar efficiency near 10 percent. Solid neodymium, which is unsuited for high-power continuous operation, has lased with solar pumping. Neodymium in liquid form provides a means of removing heat through circulation, and in this state it has lased with flashlamp pumping (ref. 22). Collisional quenching and thermal broadening of the neodymium upper states could limit efficient continuous lasing at elevated temperatures. Measurements of these effects will be made after achieving solar-pumped lasing of liquid neodymium. If required, new solvents that could provide better thermal isolation to the neodymium ion will be investigated.

Additional advanced solar-laser candidates such as  $S_2$  and  $Na_2$  are receiving preliminary study. Each of these candidates offers advantages over  $C_3F_7I$  and may lead to higher power lasing. Sulfur and sodium absorb light efficiently at the peak of the solar spectrum and also lase with narrow-bandwidth emission lines. Such lasants require high-temperature operation, which is a very advantageous condition for solar pumping.

There is much interest in using a solar-heated blackbody cavity to pump a gas laser, since this concept permits use of the entire solar spectrum. Gain from a blackbody-pumped  $CO_2$  system has been reported (refs. 23 and 24), and experiments at the University of Washington recently have demonstrated blackbody lasing of  $CO_2$  in an electrically heated cavity (ref. 17).

Two blackbody-pumped  $CO_2$  laser systems are being considered. The first system has the  $CO_2$  (and thus the laser tube) in the blackbody cavity, where it is directly pumped and lases. This concept is known simply as a blackbody-pumped  $CO_2$  laser. The second system employs a flowing gas ( $CO$  or  $N_2$ ) to absorb energy in the cavity and transfer this energy by collision to the  $CO_2$ . This concept is defined as a blackbody-pumped  $CO_2$  transfer laser.

The blackbody-pumped  $CO_2$  laser offers an estimated 10-percent solar-to-laser efficiency at very low system weight. Some system limitations are associated with thermal radiation being absorbed into the walls of the laser cavity rather than exciting  $CO_2$  to lase. However, a more fundamental problem is the need to minimize heating of the  $CO_2$  in order to avoid filling the lower laser level and thereby removing the inversion. In conjunction with an experiment to achieve pulsed low-power operation with a blackbody-pumped  $CO_2$  laser, a computational effort is planned to model the physics of this laser.

The blackbody-pumped  $CO_2$  transfer laser, which was demonstrated in principle a decade ago, avoids the problem of lasant heating by exciting a

flowing transfer gas ( $\text{CO}$  or  $\text{N}_2$ ) and achieving the required inversion through collisional excitation of the  $\text{CO}_2$ . The flow is subsonic, unlike that in a standard gasdynamic laser. This system is somewhat complex, because the transfer gases must be pumped, mixed with  $\text{CO}_2$ , and later separated for recycling. The new, efficiency-enhancing step in the process is optical excitation of the  $\text{CO}$  transfer gas. A coordinated experimental and modeling study is planned to explore the roles of isotope absorption effects, blackbody temperature, emissivity, and flow dynamics on the high-density excitation of  $\text{CO}$  to vibrationally excited levels.

Electrically stimulated and nuclear-pumped lasers are largely neglected in the current NASA laser research program. A study of free-electron lasers has defined the potential benefits of adapting the existing DOE-DOD technologies to NASA applications and has outlined the initial program for this adaptation.

Under the present program, all technologies are progressing very slowly, and only the direct solar-pumped laser is progressing at a rate that will allow definition of its potential in this decade. Whether this concept will meet all the technology requirements for a space-based laser system cannot be assessed presently. To assure a reasonable chance of achieving the technology for an efficient solar-energized laser by the end of the decade, competing concepts require attention. However, such additional research is severely restricted under the present program. Critical technologies that are severely limited at present and which should be investigated include blackbody-pumped molecular and transfer lasers and electrically energized lasers such as the free-electron laser. In summary, NASA's laser effort currently lacks the scope necessary for rapid progress. Because of manpower and resource limitations, space-based laser concepts are being researched in series rather than in parallel.

*Transmission.*—No research is being done currently on transmission optics to directly support the NASA high-power laser program. The current work in large optics is being conducted in support of the Space Telescope Project and also provides consultation support to DARPA in high-power laser optics. NASA has several facilities that can be used to support an expanded high-power laser program. Heavily funded DOD programs are developing much of the transmission, pointing, and tracking technology required for high-power laser energy transmission. There are transmission issues (such as the heating of optics resulting from continuous, high-power operation) which are not being addressed by the DOD programs, but the most prudent course of action appears to be to confine near-term NASA activities to work that is closely coordinated with DOD and to systems studies that will define technology elements that are unique to NASA mission requirements. Later, when the laser systems to be used in NASA missions are better defined, research on these elements should be initiated.

**Laser propulsion.**—The current NASA research program on laser propulsion consists of two tasks: (1) the development of mathematical models for absorption of laser radiation and formation of a laser-supported plasma in a rocket thrust chamber, and (2) an experimental study of the coupling of a CO<sub>2</sub> laser beam with hydrogen gas. This study is designed to characterize the resulting plasma and to provide experimental measurements for comparison with the mathematical models. No research is being done on competing concepts, such as laser-induced ablation plasmas (ref. 25).

Theoretical analysis of laser-supported plasmas has been pursued by NASA since the mid-1970's. The early studies (e.g., ref. 26) first addressed the mechanisms by which laser energy can be absorbed into a gas, and then moved into an evaluation of a hydrogen thruster based on a laser-supported combustion (LSC) wave. After several alternatives had been explored, emphasis was placed on a pure hydrogen system, in which a coflowing buffer gas was introduced around the hot plasma core.

The earliest analytical models for laser-supported plasmas were usually one-dimensional along the laser beam (refs. 27 and 28). A specific one-dimensional model was later extended to two spatial dimensions (ref. 29) and was applied to the laser-supported plasma in air and in hydrogen. This model is based on thermal conduction and assumes a constant value of the laser absorption coefficients above a certain "ignition" temperature. Furthermore, it assumes that the flow is at constant pressure in a cylindrical duct. An example of the calculated temperature field based on this model is shown in figure 9 (ref. 30). The plasma, contained within a 2-cm channel at 1 atm with a flow velocity of 20 cm/sec, is calculated assuming

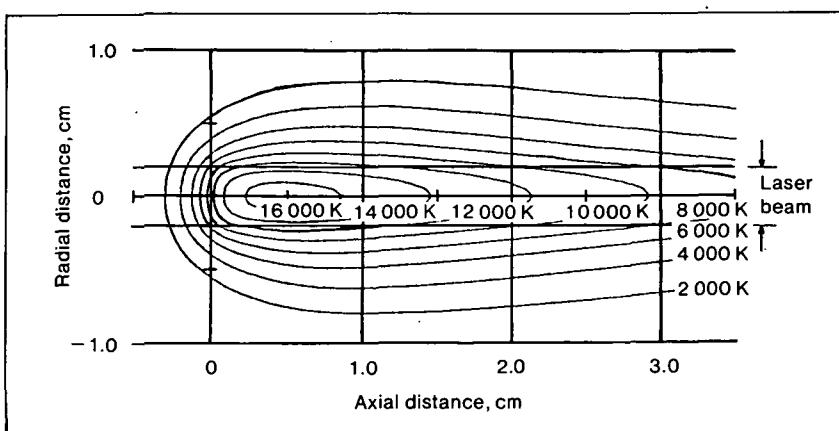


Figure 9.—Temperature field for 1-atm LSC wave in hydrogen. Laser power at 10.6  $\mu\text{m}$  is 9.1 kW. (From ref. 30.)

a 9.1-kW laser beam 4 mm in diameter. If these predictions are accurate, they indicate the feasibility of developing a successful laser thruster. However, because of important simplifying assumptions, these predictions require validation through more rigorous analyses and through experiment, as described below.

When the NASA experimental program began in 1978, it was not known if LSC waves could be established and sustained in pure hydrogen. Conrad (ref. 31) had previously observed LSC waves and examined their behavior in air using a CO<sub>2</sub> gasdynamic laser. He observed that these waves propagated up a convergent laser beam until the laser intensity was just below the threshold necessary to sustain the plasma. At this point the LSC wave disappeared. Two interesting effects were also noted. First, the solid target sustained no damage from the laser beam during the initial phase of the LSC wave, and second, a new LSC wave formed at the target and began its journey up the laser beam almost as soon as the preceding wave was extinguished. It was obvious that the LSC wave was shielding the target by absorbing the incident laser radiation. Conrad subsequently conducted experiments in which he was able to maintain the LSC wave stationary by the introduction of air flow opposite to the direction of travel of the LSC wave (ref. 32).

Because no data existed at that time for LSC waves in hydrogen, in late 1978 a joint effort was initiated by NASA Marshall Space Flight Center and the U.S. Army Missile Command to explore this area. In 1979, Conrad and Roy (ref. 32) conducted a series of experiments which showed that LSC waves could readily be established in hydrogen at lower threshold intensities than had previously been estimated.

The experimental program at Marshall Space Flight Center is planned to define the coupling of a CO<sub>2</sub> laser beam with hydrogen gas, to characterize the energy radiated from the plasma to the surrounding hydrogen and absorbed by the chamber walls, and to measure the bulk temperature of the hydrogen at the test chamber exit. The test chamber is shown schematically in figure 10. With this apparatus, steady-state laser-supported combustion waves will be produced in a focused vertical beam. During these tests, two-dimensional temperature profiles will be obtained and a spectrographic survey will be made to guide further diagnostic development.

The principal technology barrier in this area of research is the need for experimental validation of current analytical predictions for thruster phenomena and performance. The current program provides a meaningful attack on this problem, but more sophisticated experiments will be required. A new chamber is required to permit a study of flow effects on the plasma and to conduct extended measurements of the radiation from the plasma. Detailed two-dimensional measurements of plasma temperature, together with measurements of the laser beam characteristics, will permit

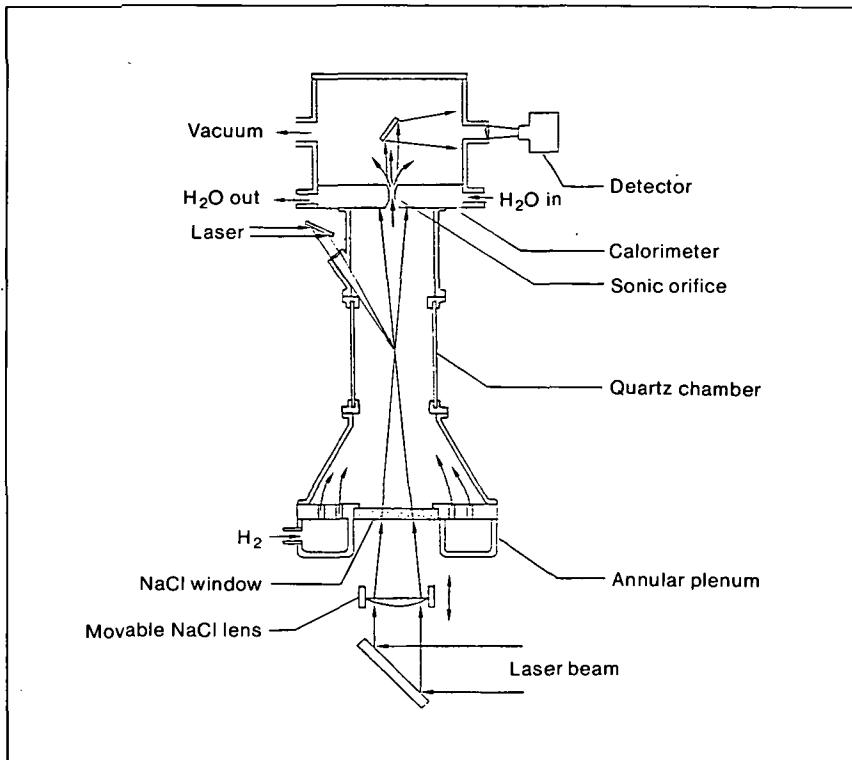


Figure 10.—Schematic of test chamber for laser-induced plasma experiments.

a comparison between the experimental results and the predictions of the two-dimensional models. Once the fundamental thruster processes have been defined, the program will concentrate on the engineering challenge of designing, building, and successfully demonstrating a thruster in the 100-kW power range.

**Laser-to-electric power conversion.**—To be practical, a laser converter must (1) be properly matched to the laser wavelength, (2) exhibit high energy conversion efficiency, (3) operate at high power density, (4) have a high ratio of peak power to system weight, (5) operate reliably, and (6) not be excessively expensive to manufacture. Of these necessary converter characteristics, the most important are wavelength match, high efficiency, and high power density operation.

Proper wavelength match between the converter and the laser is crucial to obtain high system efficiency. For example, a system that paired a GaAs photovoltaic cell with an efficient CO<sub>2</sub> laser would not be well matched. Although GaAs cells have a laser conversion efficiency greater than 40 percent near 0.85  $\mu\text{m}$  (ref. 33), the CO<sub>2</sub> laser emits near 10.6  $\mu\text{m}$ .

At the CO<sub>2</sub> emission wavelength, the GaAs conversion efficiency is zero. Thus, in general, either the converter must be carefully wavelength-matched to the laser, or the converter must exhibit high efficiency over a broad range of wavelengths.

A high conversion efficiency and the capability to operate at a high power density are closely linked. The need for good conversion efficiency is obvious. However, what happens to the fraction of energy that is not converted, especially at high power density, is a crucial question. If this power is converted to heat, high temperatures result which may reduce efficiency and require major cooling systems. Converters that transmit unconverted power rather than absorb it could have significant advantages in thermal management, efficiency, stability, and reliability. Three concepts that may satisfy these requirements are optical rectification, laser-driven magnetohydrodynamics (MHD), and a reverse free-electron laser. (See fig. 11.)

Rectification at 60 Hz using solid-state rectifiers is an extremely efficient means of converting AC power to DC. During the last two decades, rectifiers have been developed which operate at increasingly higher frequencies, so that today microwave power can be converted to DC with efficiencies greater than 50 percent. Development of an optical rectifier (i.e., an efficient rectifier operating at optical frequencies) would provide the technology to develop a small, high-power-density laser converter similar to that presently used for microwaves. A primitive, low-capacitance, optical-frequency rectifier was demonstrated in the mid-1970's (ref. 34). Its structure consisted simply of two metal strips separated by an ultrathin insulating film. This rectifier has been used as a laser mixer to produce new signal frequencies, as a harmonic generator for frequency measurement, and as an optical detector. This device remains primarily a laboratory research tool and has low power conversion efficiency in its present form. However, development of a laser converter based on this technique has a potentially high payoff for laser power transmission.

The advantages of this rectifier are its potential high efficiency due to its ability to couple energy directly from the electric field in the coherent electromagnetic wave, its low heat generation, and its insensitivity to laser wavelength. Since the structure of the device is simple, the rectifier could be easily constructed, tested, and studied. The concept for employing these optical diodes in a converter is based on the formation of an array in which the devices are connected in parallel and in series to achieve full wave rectification. Submicrometer electronics technology would be required to fabricate and install the diodes, perhaps in the walls of an optical waveguide cavity. Thus, the converter would have the simplicity and reliability of an all-solid-state device. Since the weight and manufacturing costs could be much lower than for converters requiring containment vessels, system redundancy could be practical in space. The challenge

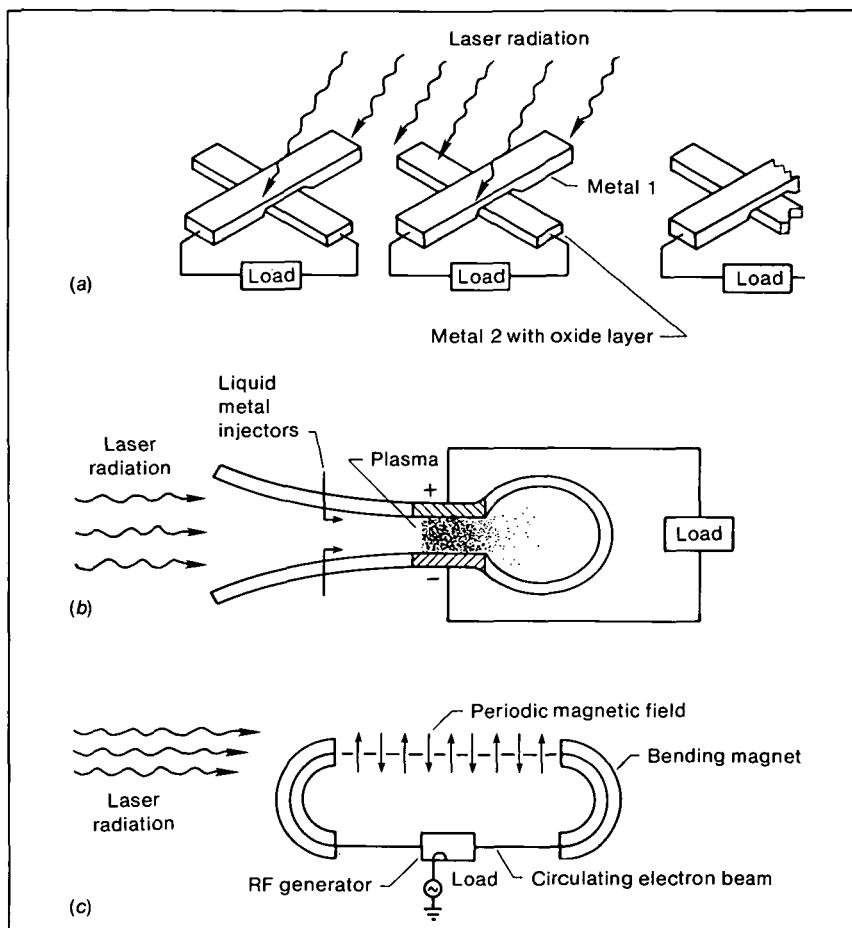


Figure 11.—Novel laser-to-electric power converter concepts. (a) Optical rectification. (b) Laser-driven MHD. (c) Reverse free-electron laser.

currently posed by a rectifying laser energy converter involves the achievement of an efficient diode. The conversion process can be divided into two steps: (1) coupling energy from the wave into the diode; and (2) efficiently extracting the electrical output internal to the diode. The efficiency for coupling energy from the wave into the diode could be estimated and optimized using the theories of optical waveguides and high-frequency antennas. The efficiency internal to the diode is difficult to measure, and it is most important that it too be assessed accurately. The upper limit for array efficiency is set by the internal efficiency of the diode. Achievement of high efficiency depends upon diodes that rectify at zero bias. Estimation of this efficiency requires identification of the dominant mechanism of

operation. Both theory and experiment are being extended to identify the material structures for limiting reverse current and the electronic mechanism that describes electron transport. With this information, a reliable conversion efficiency estimate and a plan for further research will be formulated.

Although MHD concepts and a few large operating systems have been around for quite some time, a laser-powered MHD system would be conceivable only in a space-based laser energy conversion program. The advantages of laser-driven MHD for space operation are high system efficiency, high-power-density operation, and the closed-cycle nature of the system. The high efficiency derives from the MHD internal efficiency (energy generated relative to energy deposited in plasma) of 50 to 70 percent (ref. 35) and the expected high absorption of laser energy by the plasma (ref. 36). Since the plasma characteristics can be adjusted to make the plasma a broadband absorber, this high efficiency could be achieved with a wide range of laser wavelengths. Thus, an MHD converter does not require a laser that operates at some specific resonance energy. MHD is naturally a high-power-density technique, since the input power must be sufficient to produce and sustain an ionized gas at a temperature of several electron volts. In order to achieve high efficiency and maintain a low wall temperature, the high-density power must all be absorbed in the plasma. The adjustment of plasma parameters to achieve a low-temperature (16 000 K) high-conductivity plasma constitutes the primary challenge to laser-driven MHD. An experimental and computational effort will define the laser-induced temperature, conductivity, and velocity of the plasma in terms of laser power density and MHD fluid composition. Further modeling will be done to estimate system efficiency.

A reverse free-electron laser (RFEL), as the name implies, is a free-electron laser system tuned to absorb rather than to emit coherent radiation. Although a small number of free-electron lasers are in operation, an RFEL has not been demonstrated, and development of this converter concept must begin with the laser. A free-electron laser (FEL) operates via the interaction of relativistic electrons with a spatially oscillating magnetic field to produce lasing. The advantages of a free-electron laser are wavelength tunability from the far ultraviolet to the far infrared, capability of high-power operation, and projected high efficiency (ref. 37). The disadvantages are the need for high initial electron energy and the size and mass requirements of the cavity and the magnetic field system.

The advantages of an RFEL converter are (1) it uses the coherent properties of laser radiation for conversion and thus could be extraordinarily efficient, (2) much of the power that is not converted could be reflected or transmitted and would not produce heat, (3) its wavelength tunability means that in principle it could be matched to the emission wavelength of any laser. These advantages are a powerful combination.

The challenge of making an efficient RFEL involves lowering the average electron energy so that very small energy losses in the electron acceleration system do not exceed the laser energy transferred to the electrons. The relativistic electron energies are dictated by the size and spacing of the spatially oscillating magnetic field. Although the physics of the present free-electron laser are well understood, the technology for a low-electron-energy FEL is not developed, and its requirements could exceed current technological capabilities. A theoretical exploration of advanced concepts such as a quantum beats RFEL and a miniaturized RFEL is a necessary first step toward assessing the likelihood of achieving an efficient reverse free-electron laser in the near future.

Other concepts with potential payoff are the thermoelectronic laser energy converter (TELEC) (ref. 38), narrow-bandgap semiconductors for photovoltaic cells that are sensitive in the infrared, and photon and heat engines (ref. 39). Photoelectrolysis, which uses laser irradiation to dissociate water and store energy in the form of H<sub>2</sub> and O<sub>2</sub> for eventual recombination in a fuel cell, is also being studied (ref. 40). Each converter type provides a specific set of difficult and challenging problems and options. This area of laser-to-electric power conversion is in too early and fluid a stage of development to enable selection of a "most likely" candidate. Likewise, none of the present converters has demonstrated conversion efficiencies greater than approximately 50 percent. The goal is to exceed what can be achieved by use of either photovoltaic cells (20 percent efficient) or current heat engines (35 percent efficient). A broader effort supporting competing conversion concepts in parallel is required if the feasibility and characteristics of these converters are to have feedback and impact on laser research options.

*Systems studies.*—Concepts involving high-power space-based lasers have been considered for many years (ref. 41). Satellite Power Station system studies are considering laser power transmission as an alternative to microwave transmission (refs. 42 to 44). However, most space-to-space studies have been used to promote a specific concept. A few looked at a range of applications, but most designed a single preliminary system and discussed its merits and future research needs. There is no system study available which integrates all subsystem elements into a coherent space-based system. However, until the technology base for some of the more promising new concepts (such as solar-pumped lasers) is significantly augmented, additional overall systems studies are not warranted. Accordingly, near-term systems studies should be aimed at identifying a potential application and then configuring a benchmark system study. When the technology base has been advanced significantly, a new-generation 100-MW laser system study must be carried out.

From this discussion of the present NASA laser research program, it should be clear that a number of key technology barriers must be over-

**Table IV.—Technology Barriers**

<b>Direct solar-pumped lasers</b>
Possible negative effects of elevated temperatures on quenching and recombination rates for iodide lasers
Degradation of total system efficiency due to lasant reprocessing requirements for closed-cycle operation
High threshold for continuous lasing of IBr
Depopulation of absorbing molecular level due to increase in triplet-state density in dye lasers
Potential limitation of continuous lasing due to collisional quenching and thermal broadening of upper states in liquid-Nd laser
<b>Indirect (blackbody) solar-pumped lasers</b>
Filling of lower laser level due to heating of lasant in blackbody cavity
Potential reduction of laser output in CO/CO <sub>2</sub> transfer laser due to large radiative and collisional energy losses during transfer process
<b>Transmission</b>
Lack of high-power high-temperature optics for long-term operation
<b>Laser propulsion</b>
Need for experimental validation of thruster analyses
Uncertainty regarding basic absorption mechanisms
Potential thruster design problems due to high plasma temperatures
<b>Laser-to-electric conversion</b>
Low efficiency and/or high mass of demonstrated concepts
High-conductivity low-temperature plasma (about 16 000 K) for laser magnetohydrodynamic conversion not yet demonstrated
Need to lower average electron energy range for reverse free-electron laser (RFEL)
Potential excessive mass of RFEL
Need to demonstrate high internal efficiencies for optical diode

come if the full potential of space-based high-power lasers is to be realized. These technology barriers are summarized in table IV. The goal of the proposed program presented in the next section is to address these technology barriers.

## ***Proposed Space-Based Laser Transmission Program***

The proposed program is designed to define the full potential and critical technology areas for space-based laser systems (table V). This program is not hardware-oriented; it is designed as a research program to investigate the potential of high-power lasers in NASA missions and to develop the enabling technology for space-based laser systems. The goal of this laser program is to overcome the technology barriers and develop

**Table V.—Milestones**

Program elements	Year									
	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
<b>Solar-pumped lasers</b>										
Demonstration of blackbody laser . . . . .					▲					
Demonstration of continuous-wave solar laser . . . . .						▲				
Demonstration of 1-kW solar laser . . . . .								▲		
Demonstration of 5% efficient solar-energized laser . . . . .										▲
<b>Laser energy conversion</b>										
Selection of primary-candidate laser-to-electric converters . . . . .					▲					
Demonstration of 50% laser-to-electric converter . . . . .									▲	
Characterization of H <sub>2</sub> plasma . . . . .					▲					
Thruster cooling experiment . . . . .						▲				
100-kW laser thruster experiment . . . . .									▲	
<b>Laser power transmission optics</b>										
Identification of critical-technology elements . . . . .					▲					
Complete development of critical optical components . . . . .									▲	
<b>Space-based laser systems studies</b>										
Multiple applications for space-based lasers . . . . .					▲					
Benchmark high-power laser system . . . . .						▲				
100-MW space-based system design . . . . .										▲

all the technologies involved to a point that will allow quantification of the potential of each system relative to the space-based power and propulsion requirements of future NASA missions. The program is balanced in that there is appropriate emphasis not only on laser generation but also on transmission and conversion. In addition, systems studies are included to provide focus for the major components of the program.

This proposed program is unique to NASA because most of the elements are not presently being studied by either DOD or DOE. The program objectives fall well within the interests and potential mission requirements of NASA. There is no duplication of effort with other high-power laser programs, although related technology areas being studied by DOD and DOE will be monitored and technical results from these programs will be used to supplement NASA research.

The current NASA program is primarily active in laser research. In the areas of transmission, conversion, propulsion, and systems studies, research is intermittent. The proposed program outlined in table V would constitute a significant acceleration of the work in blackbody lasers, laser propulsion, and laser-to-electric conversion. Each milestone in the table identifies a programmatic objective in its technology area. Taken together, these objectives identify a research and technology base that will serve the needs of advanced NASA missions into the 1990's and beyond.

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16. Abstract  NASA's current program in high-power space-based lasers is assessed in the contexts of potential civilian and military applications and complementary Department of Defense (DOD) and Department of Energy (DOE) efforts. Potential NASA applications for high-power lasers are reviewed. A comparison is made between NASA's technological needs and those of DOD and DOE. The current status of technology for NASA mission requirements in the areas of lasers, transmission, receivers/converters, and conceptual systems is summarized. A program outline developed by the NASA High-Power Laser Working Group presents proposed areas of research which will lead to a strong technological base for future civilian applications.		
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